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Management Effects on Soil Physical Properties in Long-Term Tillage Studies in Kansas

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ABSTRACT

Five long-term tillage studies in Kansas were evaluated for changes in soil properties including soil organic carbon (SOC), water holding capacity (WHC), bulk density, and aggregate stability. The average length of time these studies have been conducted was 23 yr. Soil properties were characterized in three depth increments to 30 cm, yet changes due to tillage, N fertility, or crop rotation were found primarily in the upper 0- to 5-cm depth. Decreased tillage intensity, increased N fertilization, and crop rotations that included cereal crops had greater SOC in the 0- to 5-cm soil depth. Only one of five sites had greater WHC, which occurred in the 0- to 5-cm depth. Aggregate stability was highly correlated with SOC at all sites. No-tillage (NT) had greater bulk density, but values remained below that considered root limiting. Soil organic C levels can be modified by management that can improve aggregate stability, but greater SOC did not result in greater WHC for the majority of soils evaluated in this study.

THE PHYSICAL PROPERTIES of any soil are a function of climate, vegetation, parent material, topography, and time. Most soils of the Great Plains have formed from parent material, such as Wisconsin loess that was deposited about 20 000 yr ago. Consequently, the soils have evolved into a balanced, stable resource capable of producing several Mg ha^{-1} of native biomass each year (Barnes and Baylor, 1995) Yet, in a very short period of time, management by man has altered this balance. For example, at Sidney, NE, breaking sod into a wheat (*Triticum aestivum* L.)—fallow rotation reduced soil organic matter content by 20% for no-till (NT), 25% for mulch till, and by 37% for plow-till in just 16 yr (Follet and Schimel, 1989). In the USA, the majority of land now in production agriculture was initially cleared and plowed to facilitate annual row crop and cereal grain production. Depending on location, plowing was common through most of the 20th century. As a consequence, by 1960 SOC levels across the Great Plains were about 52% of their original content (Donigian et al., 1994). In the late 1960s, improvements in planting equipment made it possible to plant crops without tillage, and NT agriculture was born.

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Since the 1960s, many studies have been conducted comparing NT and conventional tillage (CT) practices, as well as documenting the effect they have on soil physical, chemical, and biological properties. Use of NT systems to conserve water for crop production has made it possible to crop more frequently in the central Great Plains (Anderson et al., 1986; Shanahan et al., 1988; Halvorson, 1990; Peterson et al., 1993; Halvorson and Reule, 1994). Efficiency of water use has obviously improved, but questions remain as to the cause: improved infiltration, improved WHC, or lower evaporation.

Soil water status between periods of saturation and drought can be described by the soil water characteristic curve. As water content decreases, water is held in tension by incrementally smaller pores as tension levels increase. The distribution of soil pores is a function of soil particle size and structure. Soil particle size for a site will not change due to management, but soil structure can be influenced by soil management that may modify the shape of the soil water characteristic curve. Although this property has been extensively studied for characterizing chemical transport (Shouse et al., 1995; Williams et al., 1983; Woston and van Genuchten, 1988), the impact of tillage choice on soil water characteristic has not been well documented. Fuentes et al. (2004) showed that temporal changes of the soil water characteristic in the top 3 cm were greatest in CT (0.07 m^3 m^{-3}), with less change occurring in NT (0.036 m^3 m^{-3}) and natural prairie (0.019 m^3 m^{-3}). These authors stated that temporal changes in the soil water characteristic were more affected by seasonal moisture levels than by tillage, although their study was limited to a 1.5-yr period.

Soil degradation can occur quickly because of improper or excessive tillage, but improvements in soil structure caused by tillage selection are slow to occur, and require long-term tillage comparisons to quantify. Intensity of crop production may indirectly affect soil water characteristic by modifying SOC and increasing the turnover of SOC. Nitrogen fertilization for cereal crops typically increases stover and grain production. Greater returns of organic C to the soil as crop residue provides the potential to influence SOC levels. The resulting impact of cropping intensity on soil water characteristic needs to be assessed. The objective of this study was to quantify changes in soil physical properties due to agricultural management practices commonly thought to increase SOC.

MATERIALS AND METHODS

Five long-term study sites were selected across the state of Kansas as described in Tables 1 and 2, and located in Fig. 1.

Abbreviations: CT, conventional tillage; ET, evapotranspiration; GMWD, geometric mean weight diameter; NT, no-tillage; RT, reduced tillage; SOC, soil organic carbon; WHC, water holding capacity.

Table 1. Descriptions of research sites that were sampled to evaluate changes in soil physical and soil organic C properties.

Site	Whole plots	Subplots	Date Est.	Cropping system	Tillage description†
Ashland Bottoms	Cropping system	Tillage	1974	Continuous GS, Continuous SB, or GS-SB‡	CT: chisel, disk, field cultivator NT: chemical weed control as needed
Hays	Tillage	N rate: 0, 67 kg ha^{-1}	1965	Wheat-grain sorghum-fallow	CT: disk, mulch treader RT: V-blade sweep, rodweeder NT: chemical weed control as needed
Manhattan	Tillage	N source: Ammonium nitrate, manure	1990	Continuous corn	CT: chisel, disk NT: chemical weed control as needed
Parsons	Tillage	N rate: 0, 140 kg ha^{-1}	1983	Grain sorghum-soybean	CT: chisel, disk, field cultivator RT: disk, field cultivator NT: chemical weed control as needed
Tribune	Tillage		1989	Wheat-grain sorghum-fallow	CT: V-blade sweep RT: field cultivator NT: chemical weed control as needed

† Tillage systems varied by location, but in general CT indicates full chisel-disk tillage, RT was reduced or minimum tillage with an effort to maintain at least 30% residue after planting, and NT indicates direct seeding into previous crop residue.
‡ GS: grain sorghum; SB: soybean; W: winter wheat; F: fallow.

These sites were chosen for evaluation because of their long-term tillage histories. They were each managed by different researchers with various short-term objectives to address local questions of yield and crop rotation within their respective region of the state. Each of these sites had been farmed previous to the establishment of these experiments, with the exception of the Tribune site. At that location, native sod (short-grass prairie) was incorporated into tillage treatments, retaining native sod as a treatment. Yield data were reported elsewhere (Budde, 2004). We evaluated changes in soil physical properties and C status that occurred as a consequence of common management practices.

What is considered CT varied by location (Table 1). In fact, CT at Tribune was a V-blade sweep plow, which is the same tillage system considered as reduced tillage (RT) at Hays. At Hays, CT included a disk and mulch treader. Both Hays and Tribune had a fallow sequence, which increased the number of tillage operations as compared with the eastern Kansas locations. The eastern Kansas locations used more aggressive tillage implements such as chisel plows as CT, with a disk or field cultivator considered RT. In all locations NT was defined as chemical weed control, and direct seed placement without prior soil disturbance. For the purposes of this study, tillage type is less important than tillage intensity. So even though tillage types are not the same, at each location tillage intensity existed at either two or three levels.

Four locations utilized a split-plot randomized complete block design with four replications. At Tribune, only one phase of the rotation sequence was sampled, therefore it was analyzed as a randomized complete block. Properly suited hybrids and varieties were selected for each site as they became available. Precipitation varies widely across Kansas with 422-mm annual precipitation at Tribune to 1016 mm at Parsons (Fig. 1).

Table 2. Soil description and particle-size distribution of each site for the 0- to 5-cm depth and soil classification according to USDA.

Site	Sand	Silt	Clay	Soil type
		%		
Ashland Bottoms	9	71	20	Reading silt loam: fine-silty, mixed, superactive, mesic pachic Argiudoll
Hays	10	63	27	Harney silt loam: fine, smectitic, mesic typic Argiustoll
Manhattan	12	70	18	Kennebec silt loam: fine-silty, mixed, superactive, mesic cumulic Hapludoll
Parsons	19	68	13	Parsons silt loam: fine, mixed, active, thermic mollic Albaqualf
Tribune	13	74	13	Richfield silt loam: fine, smectitic, mesic aridic Argiustoll

All locations except Ashland Bottoms were sampled in the fall of 2002 or 2003 following the first tillage after harvest. At Ashland Bottoms, soil samples were obtained in the spring of 2004 before planting. Soil water characteristic curves were determined on intact soil samples that were obtained using a 3.5- or 7-cm deep, 7-cm diam. stainless steel core attached to a slide hammer sampler. Soil cores were obtained from the center of depth intervals of 0 to 5, 5 to 15, and 15 to 30 cm and were stored at 4°C at field water content until analysis. Tempe pressure cells with 60-kPa membrane papers (600 mbar, Soil Measurement, Tucson, AZ) were assembled around each core. Samples were first saturated from the bottom with 0.01 *M* $CaCl_2$ by applying a constant head of about 0.8 kPa (about 8 cm H_2O). Soil cores were sequentially desaturated using compressed air in pressure increments of 1.4, 3.0, 6.0, 9.2, 18.4, and 36.8 kPa. Cell weights were recorded daily, and final equilibrium weights for a pressure setting were determined by daily weight loss of <0.5 g, which typically required 3 to 4 d to achieve. Soil cores were then dried at 105°C for 24 h to determine bulk density and porosity (assuming a particle density of 2.65 g cm^{-3}). All analyses were conducted at a constant temperature of 22°C.

Higher tension water content values were determined on crushed samples passed through a 2-mm sieve and placed in a 5.5-cm ring on 0.5- and 1.5-MPa pressure plates. Samples were saturated with 0.01 *M* $CaCl_2$ and pressure was produced using N_2 gas. Samples were considered at equilibrium after 5 d.

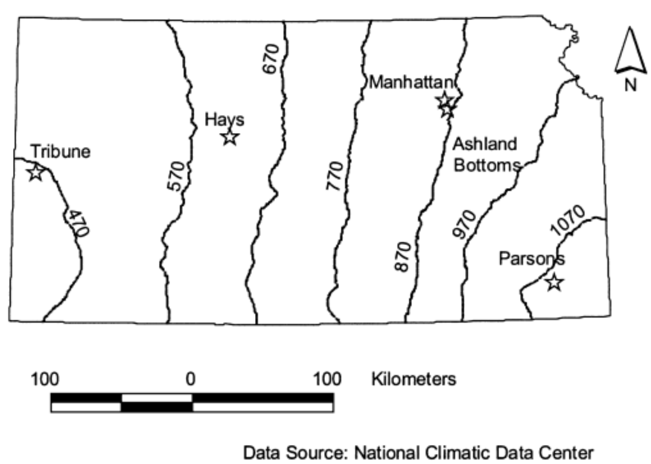

Fig. 1. Research locations and precipitation gradient (mm) across the state of Kansas using 1971 to 1999 county average annual precipitation.

Gravimetric water content was determined, and converted to volumetric basis using bulk density values from the corresponding intact cores.

Soil water characteristic curves were determined by fitting data points to the equation described by van Genuchten (1980) using RETC (J.E. Brown Jr. Salinity Laboratory, Riverside, CA). All four parameters were fit including saturated water content (θ_s), residual water content (θ_r), and two shape factors, α and N. Initial values were those appropriate for a silt loam soil as used by RETC. In some instances RETC predicted $\theta_r <$ 0.0 cm^3 cm^{-3} in which case θ_r was set = 0.0 cm^3 cm^{-3} and RETC fit the remaining three parameters. In rare cases the model fit θ_s greater than porosity, and in those cases θ_s was restricted to equal porosity and RETC fit the remaining three parameters. The average R^2 for the fit of soil water characteristic curves over all 378 cores was 0.996 with a minimum R^2 of 0.903. Using the fitted equations, WHC was estimated as the difference in volumetric water content between 9.8 kPa, and 1.5 MPa.

Aggregate stability was determined for soil in the top 5 cm of each plot. Samples were acquired using a small coring device attached to a slide hammer sampler and then passed through a 6-mm sieve to remove stones and coarse organic matter. Material < 6-mm diam. was then analyzed using the wet sieving method similar to procedures described by Yoder (1936) and modified by Mikha and Rice (2004). Geometric mean weight diameter (GMWD) of stable aggregates was calculated as described by Kemper and Rosenau (1986). Soil texture was determined for each site by the pipette method as described by Gee and Bauder (1986).

Soil organic C was determined on a composite of 8 to10 soil cores for each sample depth that were air-dried and crushed. Carbon content was determined by direct combustion using a C/N auto analyzer (Carlo Erba Instruments, Milano, Italy). Carbon mass was calculated using C concentration, bulk density values from intact cores, and soil depth.

Statistical analysis was completed using either a randomized complete block (RCB) or split-plot RCB depending on location. Unless stated otherwise, means separation are computed at the 0.05 probability level of significance using Tukey's HSD as determined with Statistix 8.0 (Analytical Software, Tallahassee, FL).

RESULTS

There were treatment effects on soil properties at the 0- to 5-cm depth primarily, with few exceptions of effects at deeper depths. This fact itself was quite surprising and significant, as the many years of differential management would have led us to predict changes in soil properties throughout the rooting depth. The results of this study suggest that measurable changes occurred only near to the soil surface; therefore all further discussion will focus on this 0- to 5-cm depth increment unless stated otherwise.

Soil organic C changes were apparent at all sites, with SOC concentration and mass greater as a function of less tillage and greater N input (Table 3). Tillage affected SOC mass at all sites except Tribune, with NT management resulting in greater accumulation of SOC than other tillage practices. Nitrogen management also impacted SOC accumulation with a difference at two of three sites where N rate was a treatment. At Ashland Bottoms, where crop rotation was evaluated, treatments that included grain sorghum [*Sorghum bicolor* (L.)

Table 3. Means of soil physical and soil organic C properties of the 0 to 5-cm depth of five long-term tillage studies in Kansas.†

Location	Treatment	θ_r	θ_s	α	N	WHC	Bulk density	SOC		GMWD
	Tillage	—— cm^3 cm^{-3} ——				cm^3 cm^{-3}	g cm^{-3}	g kg^{-1}	Mg ha^{-1}	µm
Ashland Bottoms	No-till	0.000a‡	0.415a	0.007b	1.31a	0.262a	1.31b	15.7a	10.30a	179a
	Conventional	0.008a	0.416a	0.019a	1.27a	0.229b	1.21a	11.2b	6.85b	124b
	Rotation									
	Sorghum	0.010a	0.416a	0.007b	1.34a	0.258a	1.32a	14.8a	9.83a	170a
	Sorghum/Soybean	0.000a	0.411a	0.010b	1.27b	0.248a	1.28a	15.1a	9.68a	146a
	Soybean	0.001a	0.420a	0.021a	1.26b	0.229b	1.17b	10.5b	6.12b	138a
Hays										
	No-till	0.089b	0.490a	0.156a	1.27a	0.166a	1.29a	13.3a	8.53a	228a
	Reduced till	0.105ab	0.537a	0.234a	1.29a	0.158a	1.23a	12.0a	7.37b	202a
	Conventional	0.136a	0.511a	0.116a	1.34a	0.155a	1.22a	12.5a	7.66b	190a
	Fertility									
	High	0.079b	0.517a	0.235a	1.38a	0.155a	1.22a	13.8a	8.37a	231a
	Low	0.141a	0.508a	0.103a	1.22b	0.164a	1.27a	11.4b	7.33b	182b
Manhattan										
	No-till	0.024a	0.426b	0.008b	1.29a	0.246a	1.36a	19.5a	13.08a	286a
	Conventional	0.032a	0.487a	0.041a	1.35a	0.235a	1.19b	17.4a	10.26b	199b
	Fertility									
	High manure	0.004a	0.485a	0.033a	1.24a	0.246a	1.17b	22.7a	13.35a	321a
	High Fertilizer	0.044a	0.437a	0.017a	1.41a	0.240a	1.34a	17.4b	11.70b	191b
	Check	0.042a	0.444a	0.017a	1.34a	0.237a	1.31a	15.2b	9.97c	210b
Parsons										
	No-till	0.000b	0.400a	0.012a	1.30b	0.249a	1.40a	16.0a	11.27a	372a
	Reduced till	0.006b	0.419a	0.009a	1.35ab	0.276a	1.33a	12.7b	8.44b	316ab
	Conventional	0.020a	0.414a	0.009a	1.39a	0.272a	1.41a	11.7b	8.20b	240b
	Fertility									
	High	0.004a	0.411a	0.010a	1.34a	0.267a	1.38a	13.8a	9.56a	328a
	Low	0.014a	0.411a	0.010a	1.36a	0.264a	1.38a	13.1a	9.04a	290a
Tribune										
	No-till	0.127a	0.508a	0.017a	1.57a	0.229a	1.25a	16.7b	10.43a	244a
	Reduced till	0.141a	0.524a	0.012a	1.85a	0.250a	1.20a	16.4b	9.89a	231a
	Conventional	0.122a	0.548a	0.015a	1.87a	0.263a	1.11a	15.5b	8.63a	203a
	Sod	0.104a	0.586a	0.051a	1.62a	0.195a	0.99a	22.9a	11.59a	339a

† θ_r, θ_s, α, N: Fitting parameters of the water characteristic curve as described by van Genuchten (1980). WHC: Water holding capacity; SOC: Soil organic carbon; GMWD: Geometric mean weight diameter of sand-free water stable aggregates.

‡ Means followed by the same letter are not different at the 0.05 probability level using Tukey's HSD within each location and treatment.

Moench] resulted in a greater accumulation of SOC. At this site SOC followed the same statistical patterns in the 5- to 15-cm depth (data not shown). Manhattan was the site with the greatest mass of SOC, which may be a function of manure applications at that site resulting in greater C input as compared with other sites. Although concentration of SOC at Tribune was higher in the sod as compared with the rest of the treatments, when SOC mass was calculated, there was no difference in SOC mass across all treatments. At Tribune sod retained greater SOC mass in the 15- to 30-cm depth than RT with other tillage types intermediate (data not shown).

Soil organic C concentration was highest in the native sod 14 yr after establishment compared with any of the annual crop treatments. Estimates of total SOC mass indicated no differences due to tillage treatment, although the trend was apparent that SOC concentration declined as annual cropping was imposed, with a greater rate of decline as tillage intensified (Table 3).

Only one of five sites showed a change in WHC. At Ashland Bottoms, WHC of NT was 0.03 $m^3 m^{-3}$ greater than CT. This difference represented an increase in water storage of approximately 0.15 cm in the soil profile. Crop rotation also influenced WHC at Ashland Bottoms where continuous soybean [*Glycine max* (L.) Merr.] resulted in a 0.024 $m^3 m^{-3}$ reduction in WHC as compared with rotations that included grain sorghum. At the time of sampling, the Ashland Bottoms site had been managed in this fashion for 29 yr. Although slight changes in the soil water characteristic curves were determined at other sites, these changes did not result in changes in WHC for these soils (Table 3).

Soil bulk density was greater at Manhattan and at Ashland Bottoms in NT as compared with CT management (Table 3). At Tribune bulk density of the 30- to 40-cm depth was less for sod than for CT, with NT intermediate (data not shown). In each case, bulk density values remained below that considered problematic for agricultural soils (Griffith et al., 1977; Jones, 1983).

Larger diameter stable aggregates (GMWD) were noted at three of five sites when the tillage choice was NT as compared with CT. At Parsons GMWD was intermediate for RT relative to NT and CT. The trend for GMWD was similar but not significant at Hays. At the Manhattan site, GMWD was greater with manure application. The largest GMWD aggregates were found in the sod treatment of Tribune.

DISCUSSION

At the time of sampling, these studies had been conducted for an average of 23 yr, with the longest running study (Hays) spanning nearly 40 yr. Yet measurable differences in some soil properties were detected only in the surface 0- to 5-cm depth, and were determined to be unchanged in the 5- to 30-cm depth. Tillage type likely played a roll in diluting SOC for the three eastern locations by mixing C into deeper depths. At Hays and Tribune, less mixing would have occurred because of the use of sweep plows rather than chisels so tillage induced differences in SOC were less. Still, greater levels of SOC did not consistently translate into greater WHC of the soil across sites.

Bulk density values were only minimally affected at depths below the top 3-cm of soil. At Tribune a traffic pan may have formed in CT as bulk density values at the 30- to 40-cm depth were much greater than sod or NT treatments. At Tribune, a sweep plow was used for CT, but many tillage operations at a consistent depth and tillage in general can lead to the destruction of plant roots. Without plant roots to reinforce the soil, machine-induced compaction can occur (Ess et al., 1998). Soils higher in clay content or SOC are more resistant to compaction, which may help explain why so little change in bulk density occurred at the other four locations.

Only the Ashland Bottoms location provided information on the impact of crop rotation on WHC. At that site, continuous soybean had lower WHC as compared with rotations including grain sorghum. Soybean root systems consist of shallow taproots. The fibrous root system of grain sorghum or wheat may be important for soil structure as indicated by greater WHC in the rotations including cereal crops. At this location, long-term grain sorghum yields averaged over 29 yr were more than twice that of soybean (Budde, 2004). Yield differences contributed to greater C input in those treatments that included grain sorghum, which was reflected in greater SOC (Table 3). More crop rotation studies need to be evaluated for changes in WHC.

Crop response to N applications for the three locations where N rate was a factor indicated a 48% yield increase due to N application when the crop was a non-legume (Budde, 2004). Increased C input to the soil as crop residue resulted in greater SOC at Manhattan and Hays, with Parsons showing a similar but nonsignificant trend. At Parsons, soybean constituted half of the rotation. Since soybean yielded similarly on N-rate plots (data not shown), C input for this phase of the rotation would have been similar across treatments, which helps explain the lower response seen at that location. Higher N rates resulted in greater SOC but did not affect WHC.

No-tillage resulted in greater WHC and SOC at Ashland Bottoms as compared with CT. The magnitude of the change in WHC due to tillage at Ashland Bottoms was the same as that at Tribune where the change was in the opposite direction but not significant. Several environmental factors are different between these two sites. Annual precipitation at Ashland Bottoms was twice that of Tribune. The soil at Ashland Bottoms was located within the floodplain of the Kansas River, and was of more recent geologic deposition than that at Tribune. Tribune (as well as Hays) included a fallow sequence as part of the rotation. Fallow has been shown to result in reduced C input and can lead to declining SOC levels (Campbell and Souster, 1982, Rasmussen and Collins, 1991). The Tribune experimental site had been in native grass before initiation and likely at the peak of its SOC potential, while Ashland Bottoms had been farmed for many years before experiment establishment. The potential to build SOC at Ashland Bottoms would have been greater than that at Tribune. It was also possible that WHC determination on small cores does not represent fully the water relations of the soils at each location resulting in experimental error too great to fully distinguish differences.

Components of the water balance in addition to WHC are important in overall productivity of a cropping system. Water use efficiency has been reported to be greater in RT systems as compared with CT. Sauer et al. (1996) reported the presence of residue reduced evaporation as much as 34 to 50%. Lascano et al. (1994) found in cotton production that total evapotranspiration (ET) was similar across tillage systems. But in their study large differences were found in the components of ET. The presence of wheat residue modified the microclimate, which increased transpiration to 69% of the total ET as compared with 50% for CT with no residue. This resulted in a 35% increase in lint yield.

In the northern Great Plains, Pikul and Aase (1995) found infiltration rates were greater under NT because of the protection of the soil surface. The impact of rainfall on a bare soil surface can result in substantial decrease in infiltration over very short periods of time as illustrated by Ben-Hur et al. (1998). The end result on lands with any slope is runoff and less water stored in the soil profile for later use by a crop.

Management can influence measured soil properties given enough time for differences to develop. Nitrogen additions in cropping systems dominated by cereal crops increased productivity and SOC, but did not influence WHC in this study. Tillage choice is important for managing soil C, and can influence crop yield. It is also a factor in managing crop residue and erosion control as indicated by increased aggregate stability in NT systems. Soil properties such as infiltration and evaporation potential are influenced by tillage and may be responsible for most productivity differences, especially in droughty years, or drier climes. But tillage choice did not affect WHC of most of the soils evaluated in this study, which represent soils from across Kansas.

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